ANISOTROPY OF NOTCH SENSITIVITY OF GLASS FIBRE REINFORCED PLASTICS IN LOW-CYCLE FATIGUE

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CERTIFICATE

This is to certify that the thesis entitled "Anisotropy of notch sensitivity of glass fibre reinforced plastics in low-cycle fatigue" by E.M. Somasekharan Nair is a record of the work carried out under my supervision, and has not been submitted elsewhere for a degree.

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NOMENCLATURE

K_f = Strength reduction factor

K_t = Stress concentration factor

q = Notch sensitivity

f_L = Material fringe value found for a composite laminate oriented in the 0° direction $(\frac{Kg}{cm^2} \cdot \frac{cm}{fringe})$

f_T = Material fringe value found for a composite laminate oriented in the 90° direction $(\frac{Kg}{cm^2} \cdot \frac{cm}{fringe})$

f_{LT} = Shear fringe value $(\frac{Kg}{cm^2} \cdot \frac{cm}{fringe})$

f_α = Material fringe value for any fibre orientation angle $(Kg/cm^2 \cdot \frac{cm}{fringe})$

α = Angle between fibre orientation and stress direction (degrees)

r = Radius of notch (cm)

w = Width of specimen (cm)

σ_t = Tangential stress (Kg/cm^2)

N_α = Fringe order

h = Model thickness (cm)

θ = Angle along the notch boundary (degrees)

W'	=	Width across boundary of notch (cm)
E_L	=	Modulus of elasticity of a composite with fibre orientation angle equal to 0^o (Kg/cm^2)
E_T	=	Modulus of elasticity of a composite with fibre orientation angle equal to 90^o (Kg/cm^2)
G_{LT}	=	Shear modulus (Kg/cm^2)
ν^{LT} ν_{TL}	=	Poissons ratios
σ_T	=	The applied stress (Kg/cm^2)
δ	=	Extension (cm)
f_σ	=	Material fringe value for isotropic material $(\frac{Kg}{cm^2} \cdot \frac{cm}{fringe})$

SYNOPSIS

Glass fibre reinforced plastics are being used extensively, as modern engineering materials. The design of engineering components require a thorough knowledge of the materials used particularly when they are subjected to a number of load or displacement cycles. The problem of fatigue failure becomes more complicated when a stress concentration is present. In the present investigation the study of anisotropy of notch sensitivity of a glass reinforced epoxy laminate, in the low-cycle region was undertaken.

Static and stress controlled direct stress fatigue tests were conducted on an Instron machine for a bidirectionally reinforced composite, for 0°, 15°, 30° and 45° fibre orientations. For each fibre orientation three notch sizes were tested. All specimens were tested at a constant cross head speed of 0.5 cm per minute. The notch sensitivity was found to be strongly dependant on fibre orientation. The biggest notch exhibited notch-strengthening for 30° and 45° orientations.

To study the effect of matrix material on the behaviour of composites, a few polymers have been tested for

static loading. The biggest notch exhibited notch-strengthening for CY 230 matrix while the LY 556 matrix showed notch-weakening. Polycarbonate and perspex also exhibited notch strengthening for the biggest notch. LY 556 matrix showed higher notch sen-siticity for the smallest and intermediate notches, while for the biggest notch it exhibited reduced notch sensitivity.

The CY 230 matrix (with 12% hardener) was tested for low-cycle stress controlled direct stress fatigue and exhibited notch-strengthening for the biggest notch throughout the range of cycles (1-1000). A bidirectionally reinforced composite was fabricated from the same CY 230 matrix. Notched and un-notched specimens were tested for 0° and 45° orientations. The 45° orientation exhibited notch strengthening without any 'necking'. The 0° orientation exhibited weakening for all notch sizes tested.

Notch sensitivity was found to be strongly dependent on fibre orientation for the bidrectionally reinforced com-posite. Notch-strengthening was found to be more pronounced in the case of 45° orientation. This notch-strengthening effect was observed without the absence of any 'necking'.

CHAPTER-I

INTRODUCTION

Glass fibre reinforced plastics are being used extensively as modern engineering materials because of their many desirable properties such as high specific strength (strength/weight), high specific modulus, resistance to corrosion and the ability to provide reinforcement in any required direction. Some of their applications are in aircraft landing gear, helicopter rotor blades, storage containers for chemicals and vehicle bodies. The use of glass fibre reinforced materials in load bearing structural applications depends often on their ability to withstand cyclic loading, especially when the structures are subjected to a number of load or displacement cycles during their life. The fatigue behaviour can be controlled by proper choice of fibres, resins and fibre orientation. The problem of fatigue failure becomes more complicated when a stress concentration is also present.

The fatigue characteristics of metals are well understood. In static loading of ductile metals the increased stress at the root of the notch causes yielding, thereby

reducing stress concentration. Because of yielding, the stress becomes nearly uniform inspite of the notch. Under fatigue loading, however, much less plastic deformation occures; consequently the range of stress remains considerably higher at stress concentrations than in the surrounding material resulting in a reduced fatigue strength. Therefore stress raisers retain much of their full effect in fatigue. Although fatigue strength is considerably reduced by geometrical stress concentrations, the reduction is often less than the stress concentration factor, K_t, and a fatigue strength reduction factor, K_f , has therefore been introduced, which is defined as the ratio of the fatigue strength of a specimen with no stress concentration, to the fatigue strength with stress concentration. A measure of the degree of agreement between K_f and K_t is given by the notch sensitivity factor , q. which is defined as

$$q = \frac{K_f - 1}{K_t - 1} \qquad \ldots. \qquad (1)$$

when $K_f = K_t$, $q = 1$ and material is said to be fully notch sensitive. If the presence of a notch does not affect the fatigue strength, $K_f = 1$ and $q = 0$ and the material is notch insensitive. It is found, however, that the value of notch sensitivity, q, depends not only on the material but also on the stress conditions, the size of the specimen or

part and the endurance, so that q cannot be regarded as a material constant. The static tensile strength of a notched specimen is often (in the case of ductile metals) higher than the unnotched tensile strength, because of the triaxial stress system at the notch and the smaller volume of material subjected to the maximum stress in the notched specimen (1). In fatigue the S - log N curves for notched and unnotched specimens converge as the number of cycles to fracture is decreased and may cross at an endurance between 1 and 1000 cycles. Thus the notch sensitivity may become negative at low endurances.

In the case of glass fibre reinforced plastics it was generally concluded that a stress raiser was fully effective in initiating damage but the effect on ultimate failure was small. Early work of Boller (2) and recent investigations by Owen (3) and J.W. Davis, et al.(4) also support the above conclusion.

Dally and his co-workers (5) pointed out that the damage at the root of the notch resulted in a changed notch geometry, leading to a reduction in the value of the stress concentration factor, thereby reducing the notch sensitivity. Prabhakaran (6) has recently shown that while a low notch sensitivity may be exhibited by glass fibre reinforced plastics in general, it is possible for some of them to be almost

fully notch sensitive and for others to exhibit even a negative notch sensitivity (notch-strengthening). Broutman and Sahu (7) have shown that fatigue fracture in fibrous composites depends strongly upon the properties of the matrix material.

An experimental study of the anisotropy of notch sensitivity in low cycle fatigue of a particular glass fibre reinforced epoxy was undertaken in the present work. The fibre orientation angle was an important parameter in the investigation. A study of the notch sensitivity under static loading of a few polymers, including some varieties of epoxies, was also undertaken. A bidirectionally reinforced composite fabricated from one variety of epoxy was also tested under static load. The same matrix material was tested both for static and low cycle fatigue loading.

Literature Survey:

Of the various thermosetting resins commonly used in glass fibre reinforced plastic laminates, the best fatigue properties are obtained with epoxy resins (8). This superiority is attributed to the inherent toughness and durability of epoxy resins, high mechanical strength, low shrinkage during cure and excellent adhesive properties. The effect of filament orientation for nonwoven reinforcement has been investigated by Bollor (9). Maximum single cycle strength occurs when all

the glass fibres are parallel to the load, and as some of the glass fibres are oriented normal to the load direction, the strength decreases (10). However, for alternating stresses, at 10^7 cycles the laminate with all the glass fibres parallel to the load direction exhibits the lowest fatigue strength compared to the laminate with 85% or 71% fibres parallel to the load direction. A similar effect is observed for the case of alternate fibre plies oriented symmetrically at small angles to the load direction. The fatigue strengths are highest when the plies are oriented at $\pm$ 5 degrees to the load axis, and at $\pm$ 15 degrees the fatigue strength becomes less than that of the 0 degree oriented composite.

Optimising the static strength of a glass fibre reinforced plastic doesnot also optimise its fatigue strength. Boller (11) reports that glass fabric laminates (181 glass fabric) stressed at 45 degree to the warp direction possess a true endurance limit which begins at approximately 40,000 cycles. However, these same laminates stressed in the warp direction possess no endurance limit through 10^7 cycles. For the laminates stressed at 45 degree, the resin matrix carries much of the load in shear between the glass fabric layers, and the fatigue curve is more indicative of the resin behaviour than for the laminates stressed in the fibre direction.

Pipes and Pagano (12) found that interlaminar shear stresses and normal stresses exist near the lateral edges. It is argued that the interlaminar normal stresses as well as the interlaminar shear stresses are instrumental in precipitating delamination and subsequent strength degradation. Severe delamination has infact been witnessed by Foye and Baker (13) who identify progressive delamination as the primary source of strength degradation in fatigue. The behaviour of anisotropic materials is quite dependent on the direction of shear (14).

For a particular bidirectionally reinforced laminate with $\theta = 0^{o}$, Prabhakaran (6) has found that there was some delamination and relatively low notch sensitivity. For the same composite along the 45 degree direction there was much more delamination and notched specimens exhibited higher static strength and fatigue strength compared to unnotched specimens. Whereas in Ref. (6), the notch-strengthening effect (or negative notch sensitivity) was accompanied by a very unusual phenomenon of 'necking', Prabhakaran and Somasekharan (15) have recently shown that notch strengthening for the 45^{o} orientation can occur without 'necking'.

Levy et al (16) have numerically investigated the effect of a circular hole in a composite laminate and found

that interlaminar shear and normal stresses were present at and near the free edges of a hole in addition to the increased in plane stresses due to the stress concentration effect. Daniel et al (17) observed very high strain concentration near the hole of a 0/+ 45/0/90 plate specimen with a circular hole. Strain gauge data indicated that strains increased rapidly and nonlinearly at points on the hole boundary while linear deformation was still occurring at other points on the specimen.

J.W. Dally et al (18) conclude that stress controlled and strain controlled fatigue tests are equivalent in terms of fatigue life in low-cycle fatigue studies of glass fibre reinforced plastics. While this conclusion was reached on the basis of tests on unnotched specimens, Prabhakaran and Sridhar (19) have shown that the same conclusion is valid for notched specimens.

Stacking sequence variations have been found (20) to alter the modes of failure from catastrophic to noncatastrophic. The observed difference in laminates of same construction but varying stacking sequence are attributed to interlaminar stresses near the free edge. The most influencial of these stresses are the interlaminar normal stresses. When a laminate is subjected to an axial stress, the difference in Poissons ratio between the various plies results in transverse stresses. The stresses are equilibrated by interlaminar shear

stresses and couples produced by interlaminar normal stresses. When the outer plies are in transverse tension the interlaminar normal stresses near the free boundary are tensile, tending to delaminate the composite and therefore decrease its strength. The opposite is true when outer plies are in transverse compression. Stacking sequence variations also introduce variations in resudual thermal stresses. Whenever the free boundary contains a region of high stress concentration forcing initiation of damage in that region, the effect of stacking sequence variation and strength are further accentuated. Strain concentration factors measured with miniature gauges on the boundary of the hole were significantly different for different stacking arrangements. The corresponding strength varies inversely with strain concentrations.

The determination of stress concentration factors for various fibre orientations and for different notch parameters is described in the next chapter.

CHAPTER-II

DETERMINATION OF STRESS CONCENTRATION FACTORS

Stress concentration factors for various notch geometries in anisotropic materials are not as readily available as in the case of isotropic materials. Theoretical solutions are scarce and are confined to notches in infinite plates (21). While numerical solutions and experimental methods are more suited for anisotropic materials, such results are also not readily available. In this chapter, the transmission photoelastic technique of determining stress concentration factors in composite materials is briefly described.

As the notch sensitivity was experimentally determined for bidirectionally reinforced (balanced: equal reinforcements in both directions) composites in the 0°, 15°, 30° and 45° orientations, the elastic stress concentration factors were determined for these orientations by employing the methods of photo-orthotropic elasticity developed recently (22, 23, 24).

The model material utilised was an E-glass-fibre-reinforced polyester, with the matrix, specially blended to

produce a refractive index almost exactly equal to that of the reinforcement. Photoelastic calibration specimens (for tensile loading) for 0^o, 45^o and 90^o were machined and material fringe values were determined in a transmission polariscope using sodium light. They are

$$f_L = f_o = 207 \ \frac{Kg}{cm^2} \cdot cm/fringe$$

$$f_{45^o} = 75 \ \frac{Kg}{cm^2} \cdot cm/fringe$$

$$f_T = f_{90^o} = 195 \ \frac{Kg}{cm^2} \cdot cm/fringe$$

The material fringe values for any fibre orientation angle (for uniaxial stresses) can be calculated using the equation

$$\left(\frac{1}{f_\alpha}\right)^2 = \left(\frac{\cos^2\alpha}{f_L} - \frac{\sin^2\alpha}{f_T}\right)^2 + \frac{\sin^2 2\alpha}{f_{LT}^2} \qquad (2)$$

where α is the fibre orientation angle with the stress direction. The usual approximation (good to about 2% or better) that f_{LT} and f_{45} are equal is made. The material fringe value is shown as a function of the fibre orientation angle in Figure 2.1.

Semi-circular side notched specimens were machined from the photoelastic model material with notch parameters

$\frac{2r}{w}$ = 0.130, 0.375 and 0.740. The specimen geometries are given in Figure 2.2. Each specimen was loaded in tension and the resulting isochromatic fringe patterns were photographed. There was no residual isochromatic response because of the balanced construction. The maximum fringe order on the notch boundary gives directly the maximum tangential stress, σ_t, in isotropic materials. In the case of anisotropic materials, the variation of material fringe value along the notch boundary also has to be considered. The maximum tangential stress is given by

$$(\sigma_t)_{max} = \frac{(N_\alpha \cdot f_\alpha)_{max}}{h} \tag{3}$$

where h is the model thickness. The fringe order, N_α, the material fringe value, f_α, and the product of N_α and f_α were shown as a function of θ, along the boundary of the notch for 15° fibre orientation and notch parameter $\frac{2r}{W}$ = 0.375 in Figure 2.3 where θ, r and w are the angle along the notch boundary, notch radius and width of the specimen respectively. The stress ratio $\sigma_t/\sigma_{nominal}$ varies along the boundary of the notch and need not be, in general, maximum where σ_t is maximum. The maximum value of the stress ratio was taken as the stress concentration factor, K_t. The stress concentration factor is given by

$$K_t = \frac{(N_\alpha \cdot f_\alpha \cdot w^1)_{max}}{P} \tag{4}$$

CHAPTER-III

NOTCH SENSITIVITY OF A COMMERCIAL COMPOSITE

The anisotropy of notch sensitivity was studied for a commercial laminate. Prabhakaran (6) had tested a commercial laminate and found out that for the 0° orientation the notch sensitivity was quite small (as most of the investigators have concluded and generalized for composites) but that for the 45° orientation the notch sensitivity was negative and accompanied by a very unusual 'necking' phenomenon. In this chapter test results for the 0°, 15°, 30° and 45° orientation of a commercial composite are given.

3.1 Characterisation of the Material:

The glass fibre reinforced plastic material studied in this investigation was a bidirectionally reinforced laminate with almost equal amounts of reinforcement in two perpendicular directions. The fibre volume fraction, determined by resin burnout test, was 36.5 percent.

Five intrinsic macroscopic in-plane material properties E_L, E_T, ν_{LT}, ν_{TL} and G_{LT} are required for the characterisation of an orthotropic material. The method suggested

by Greszczuk (25) was used to measure these five elastic constants. Three tensile specimens were machined, one each for fibre orientations of 0°, 45° and 90°. Two strain-gauges, one axial and another transverse were fixed on each test specimen and tested in an Instron machine. Once the stress-strain relationship is established, the determination of elastic constants is straight forward. The shear modulus G_{LT} was obtained from the relation

$$G_{LT} = \frac{\sigma}{2(e_x - e_y)} \tag{4}$$

where e_x and e_y are the strains recorded in the loading and transverse directions of 45° specimen and σ is the applied stress. The measured elastic constants are given below:

$$E_L = 0.222 \times 10^6 \ Kg/cm^2$$

$$E_T = 0.196 \times 10^6 \ Kg/cm^2$$

$$\nu_{LT} = 0.203$$

$$\nu_{TL} = 0.181$$

$$G_{LT} = 0.042 \ Kg/cm^2 .$$

3.2 Testing Procedure:

Test specimens were prepared from commercial laminate (60 cms X 60 cms X 0.32 cm) made of E-glass fabric and epoxy matrix. All specimens were 15 centimeters long. Static and stress-controlled low cycle direct stress fatigue tests

were performed on an Instron machine. Unnotched and notched specimens were tested. Notched specimens consisted of semi-circular side notched strips approximately 2.54 cm wide. The three notch sizes tested had notch parameters $\frac{2r}{w} = 0.130$, 0.375 and 0.740 where r is the radius of the notch and w is the width of the specimen. For each fibre orientation angle a total of 48 specimens were tested, 12 for unnotched and 12 for each notch size. As the composite tested was bidirectionally reinforced and almost balanced, the specimens were tested for 0°, 15°, 30° and 45° fibre orientations. For all the tests, the cross head speed was maintained at 0.5 cms/minute. Throughout the test the frequency was kept low (1 - 6 cycles/minute) to avoid hysteresis heating.

3.3 Results for Commercial Laminate:

The S-log N curves for unnotched and notched specimens were obtained for 0°, 15°, 30° and 45° fibre orientations and are shown in Figures 3.1, 3.2, 3.3 and 3.4. The static strength values (taken as the fatigue strength corresponding to N = 1) were obtained as the average of three test results. Dally (18) on the basis of a regression analysis, found that a straight line gave the best fit for the low-cycle fatigue data for composites. In this investigation also, best fitting straight lines were obtained using the method of least squares to represent the fatigue data.

The fatigue strength reduction factor K_f was calculated for each notch and for each fibre orientation. The fatigue strength of notched specimens was taken as the nominal stress causing fracture and was obtained by dividing the load (which was maintained constant throughout a particular test in order to achieve stress-controlled fatigue loading) by the area of cross-section at the point of crack initiation. The location of the point at which the macroscopic crack initiated was determined for each fibre orientation and notch size. It was noticed that this location was independant of the notch size and depended only on the fibre orientation angle. The results for the crack initiation site are given in Table 2.

TABLE 2

Fibre orientation angle (measured from vertical) degrees	Crack initiation site angle (measured from vertical) degrees
0	90
15	85
30	85
45	85

The notch sensitivity, q was also computed from equation (1). The notch sensitivity for different notch parameters are shown as a function of fibre orientation

angle, for N = 1 and N = 500 in Figures 3.5 and 3.6 respectively. The phenomenon of notch strengthening was observed both in static and fatigue loading in certain cases but 'necking' was totally absent. The beneficial effect was seen to be more pronounced in the case of 45° fibre orientation and notch parameter $\frac{2r}{W} = 0.740$. For the sharpest notch, notch sensitivity was positive for all the angles but it was maximum for 15° and then decreased as the fibre orientation angle increased. The intermediate notch exhibited strengthening for 45° orientation but for 0° orientation the notch sensitivity was higher than that for the sharpest notch. Thus there appears a "size effect". For the intermediate notch, the notch sensitivity was found to be maximum at 0° fibre orientation and decreased as the fibre orientation angle was increased. For 45° fibre orientation intermediate notch exhibited notch-strengthening. For the biggest notch, the notch sensitivity was found to be decreased as the fibre orientation angle was increased upto about 15°, while for 30° and 45° fibre orientations, notch strengthening was observed. Notch sensitivity data for N = 500 was similar to that for N = 1 .

As the properties of a composite are greatly influenced by those of the matrix, the notch-sensitivity of

some polymers has been studied, in an effort to understand the unusual phenomenon of notch strengthening in composites. This work is described in the next chapter.

In this chapter, the anisotropy of notch-sensitivity for a commercial laminate has been described. It has been shown that for some of the fibre orientations and for some of the notch parameters, there is a notch-strengthening effect. And this strengthening effect was not accompanied by any 'necking'. Finally a size effect has been observed.

CHAPTER-IV

NOTCH SENSITIVITY OF SELECTED POLYMERS

For a balanced bidirectionally reinforced composite the role of the matrix becomes most important for 45° orientation. Thus it is reasonable to expect that the notch-strengthening effect which is predominant for this orientation, is due to the matrix. This could not be confirmed for the composite tested, as the matrix material used in its fabrication could not be obtained from the supplier. So the notch sensitivity study of a few polymers was undertaken.

4.1 Materials and Testing Procedure:

Using epoxy resin CY 230 (Batch 1) a number of epoxy matrices were cast by varying the hardener (HY 951) percentages from 8 to 25. Unnotched and notched specimens machined from the above cast sheets which were cured at room temperature, were post cured at $100^{\circ}C$ for four hours. Notched and unnotched specimens were also prepared from polycarbonate, perspex and another variety of epoxy matrix, LY 556. It was ensured that no residual birefringence was present before testing. All specimens were tested in an Instron machine under static load

at a crosshead speed of 0.5 cm per minute. The CY 230 matrix (Batch 2) with 12% hardener composition was tested for low-cycle fatigue loading also.

4.2 Results:

The stress-extension curves for unnotched specimens cast from the CY 230 epoxy matrix with different hardener percentage are shown in Figure 4.1. The stress-extension curves for the second epoxy resin, LY 556, polycarbonate and perspex are compared with the curve for the CY 230 resin cured with 12 percent hardener, in Figure 4.2.

For the CY 230 epoxy, as the hardener percentage was increased from 8 to 14 percent, the ultimate strength steadily increased but beyond 14 percent, there was a decrease in the ultimate strength for the 18 and 25 percent compositions. The fracture strength also varied in a similar manner with the hardener percentage but its decrease beyond 14 percent was steeper, with the 25 percent composition exhibiting the lowest fracture strength for all compositions. These conclusions are clear from Figure 4.1

The LY epoxy resin exhibits a relatively small extension at fracture compared to the other polymers. Polycarbonate, as Figure 4.2 shows, is the most ductile of the polymers tested. Perspex exhibited the maximum strength.

The ultimate strength for the unnotched and notched specimens are shown as a function of hardener percentage for the CY 230 resin in Figure 4.3. It is seen from this figure that the strength of notched specimens, with notch parameters $2r/w = 0.740$ and 0.375, is consistently higher than the unnotched strength, thus exhibiting a notch-strengthening effect. Results for the fracture strength were similar to the above results for the ultimate strength and are not shown.

The notch sensitivity is shown as a function of the hardener percentage in Figure 4.4. This figure shows the notch sensitivity based on the ultimate strength as well as on the fracture strength.

Based on fracture strength, the notch sensitivity of the biggest notch reached minimum in magnitude at a hardener percentage of about 14. For the intermediate notch, notch strengthening based on fracture strength was found to be more as the hardener percentage was increased from 10 to 25. Here the fracture strengths were calculated based on fracture load by the original area of cross-section.

The notch sensitivity of all the resins (CY 230 resin with only 9% hardener) is shown as a function of the notch parameter $2r/w$, in Figure 4.5. It is seen that for the smallest notch the notch sensitivity is positive for all the

polymers tested; it is a minimum for polycarbonate which is a very ductile thermoplastic polymer and is maximum (indicating almost full notch sensitivity) for LY 556 epoxy which behaves as a brittle thermosetting polymer. For the biggest notch, polycarbonate perspex and CY 230 epoxy exhibit notch-strengthening effect whereas LY 556 epoxy shows a reduced notch-weakening effect. It is surprising that perspex, which is commonly considered as a brittle thermoplastic, exhibits negative notch sensitivity but it should be recognized that there are different grades of perspex - some grades, for instance exhibiting almost complete photoelastic insensitivity ($f_\sigma \approx \infty$) and some grades showing much higher photoelastic sensitivity ($f_\sigma \approx 52 \frac{Kg}{cm^2}$ .cm /fringe). It is remarkable that polycarbonate, a very ductile polymer, is appreciably notch-sensitive. For polycarbonate the fracture strength was calculated based on fracture load and final deformed area of cross-section.

The CY 230 resin with 12% hardener (Batch 2) was tested in low-cycle fatigue. The S-log N curves for the unnotched and notched specimens are shown in Figure 4.6. The notch sensitivity was computed from these figures and is shown as a function of cyclic life in Figure 4.7. It is seen from this figure that the notch sensitivity for the smallest and intermediate notches is positive for static as well as fatigue

loading whereas for the biggest notch q is negative for $1 \leq N \leq 1000$. The notch strengthening effect decreases with increasing fatigue life for the biggest notch. The difference in the behaviour of the intermediate notch in Figures 4.6 and 4.7 is due to the fact that the specimens were prepared from different batches.

In this chapter the notch sensitivity for a variety of resins has been studied in static loading and negative notch sensitivity has been observed for certain resins and for certain notches. One resin has been tested in low-cycle fatigue and again negative notch sensitivity has been observed. In the next chapter the results for the composite prepared from this resin (which exhibited negative notch sensitivity both in static and fatigue loading) are given.

CHAPTER-V

INFLUENCE OF MATRIX ON THE NOTCH SENSITIVITY OF COMPOSITES

The notch sensitivity of a few polymers has been described in the previous chapter. The notch sensitivity of a bidirectionally reinforced composite is influenced by matrix material and fibre orientation. The bidirectionally reinforced commercial laminate exhibited notch-strengthening for the biggest and intermediate notches, in the case of 45° orientation. The composition of the epoxy matrix used for the commercial laminate was not available. So to study the effect of matrix material on notch sensitivity, a particular epoxy matrix was selected and bidirectionally reinforced composite laminate was fabricated. The notch sensitivity behaviour of this matrix under static and low-cycle fatigue loading was described in the previous chapter. In this chapter, the notch sensitivity study of the composite prepared from the same matrix is described.

5.1 Testing Procedure:

Bidirectionally reinforced composite laminates were fabricated using CY 230 epoxy cured with 12% hardener (Batch 2). The reinforcement was in the form of a glass fabric with almost

equal amounts of glass in the two directions. Notched and unnotched specimens were prepared, both for 0° and 45° orientation. Notch parameters were kept the same as those for the commercial laminate.

All the specimens were tested in an Instron machine under static loading at a cross head speed of 0.5 cm per minute.

5.2 Results:

The stress-extension diagrams for unnotched specimens of the matrix and composite with 0° and 45° orientation are shown in Figure 5.1. The stress-extension diagram for the 45° orientation was found to be closer to that of the matrix. The stress-extension relation of 0° composite was found to be almost linear upto fracture, but the curves for 45° composite and matrix were found to be significantly non-linear. For 45° composite the stress increased to a maximum value and then decreased to the fracture stress, but for the matrix such a behaviour was not found. The extension at fracture was found to be maximum for the matrix, minimum for the 0° composite. The extension at fracture for the 45° composite was about three times that of the 0° composite, but less than that of the matrix.

The notch sensitivity, q for the matrix, 0° composite and 45° composite for static loading were shown in Figure 5.2. The notch sensitivity of the 0° composite was found to be positive for all the three values of the notch parameter while that for 45° composite was found to be negative for all the three notch sizes. For the 0° composite the notch sensitivity was found to be minimum for the biggest notch while maximum occurred for the intermediate notch. For the 45° orientation smallest notch was almost notch insensitive while the intermediate notch and biggest notch exhibited notch-strengthening.

In this chapter limited results have been given to show the role of the matrix in the composite behaviour. It has been shown that for a matrix which exhibited negative notch-sensitivity in static and fatigue loading, the corresponding bidirectionally reinforced composite exhibited positive notch sensitivity (notch weakening) for the 0° orientation and negative notch sensitivity (notch strengthening) for the 45° orientation.

It should be noted that due to lack of time, results for the composite with the CY 230 epoxy under fatigue loading and for the composite with the LY 556 epoxy under static and fatigue loading could not be obtained.

The important conclusions drawn from the available results are summarised in the next chapter.

CHAPTER-VI

CONCLUSIONS

A systematic study of the anisotropy of notch sensitivity has been conducted in this investigation. While previous studies by other investigators have concentrated on the notch sensitivity of bidirectionally reinforced composites for the 0° orientation, experimental results for the other orientations have been scarce. While it has become routine practice to specify the elastic moduli and static strength (and less frequently the fatigue strength also) as a function of the fibre orientation angle, the notch sensitivity has not so far been given its due importance in relation to its anisotropy. The notch parameter, $2r/w$, has been treated as the parameter in this investigation.

Published literature on the fatigue of composites - with the exception of the recent work by Prabhakaran - is almost unanimous in concluding that composites have a lower notch sensitivity compared to metals. In the case of metals, it has been recognized that the notch sensitivity can be negative for static and low-cycle fatigue loading, especially for

ductile metals. The variation of notch sensitivity with the fatigue life for two ductile metals is shown in Figure 6.1. The basic fatigue data for this figure is taken from Ref. (1).

The present investigation confirms that composites also (for certain orientations) can exhibit negative notch sensitivity. Besides it is shown that such a notch strengthening effect can occur without the unusual phenomenon of 'necking'.

An attempt has been made to relate the notch sensitivity of the matrix to that of the composite, especially for the 45° orientation. The epoxy resin, with the manufacturer's designation CY 230, was found to exhibit negative notch sensitivity under static and low-cycle fatigue loading. The bidrectionally reinforced composite fabricated from this matrix also exhibited negative notch sensitivity for the 45° orientation, under static loading. For the 0° orientation, the notch sensitivity was positive but small, in agreement with the general conclusion of previous investigators.

While no tests have been conducted on composites with the LY 556 matrix (which exhibited appreciable notch sensitivity) in this study, published results by Prabhakaran indicate that such a composite exhibits, for the 0° orientation, high notch sensitivity. Results for the 45° orientation are not available

but it appears reasonable to expect that the notch sensitivity for this case should be positive but smaller than that for the 0° orientation.

The choice of a matrix for a composite is based on its various properties such as strength (static and fatigue), and ductility. As a result of the present investigation, it is suggested that the notch sensitivity also should be considered in the selection of the matrix; while loading at 45° to the reinforcement direction is undesirable but often inevitable, the notch strengthening effect in this direction can be used to the designer's advantage. Further work is required to identify the factors responsible for the notch strengthening effect and to evolve ways of making use of this effect in designing composite structures against fatigue.

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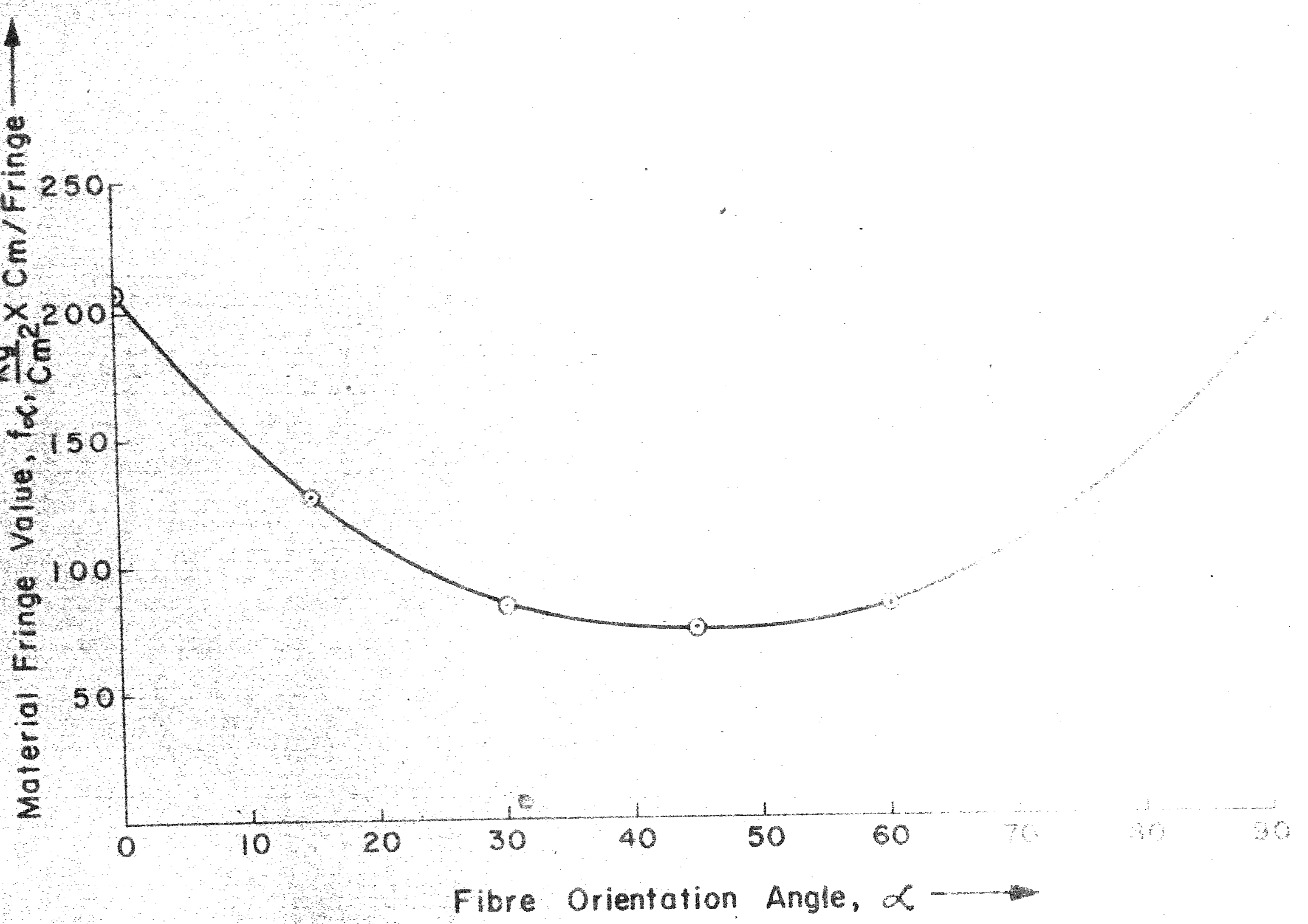

Fig.2.1 Material Fringe Value As A Function Of The Fibre Orientation Angle

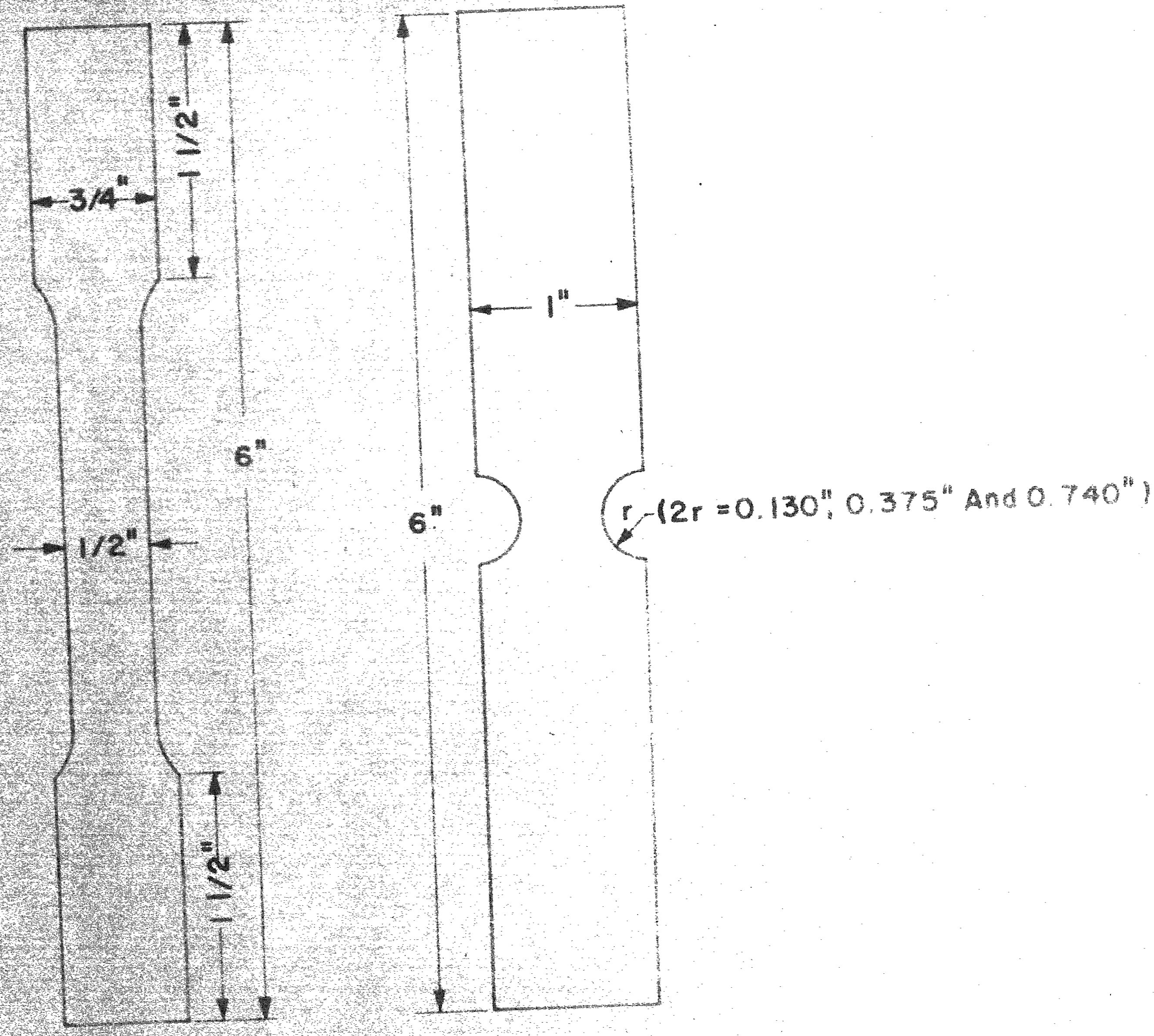

Fig. 2.2 Specimen Geometries

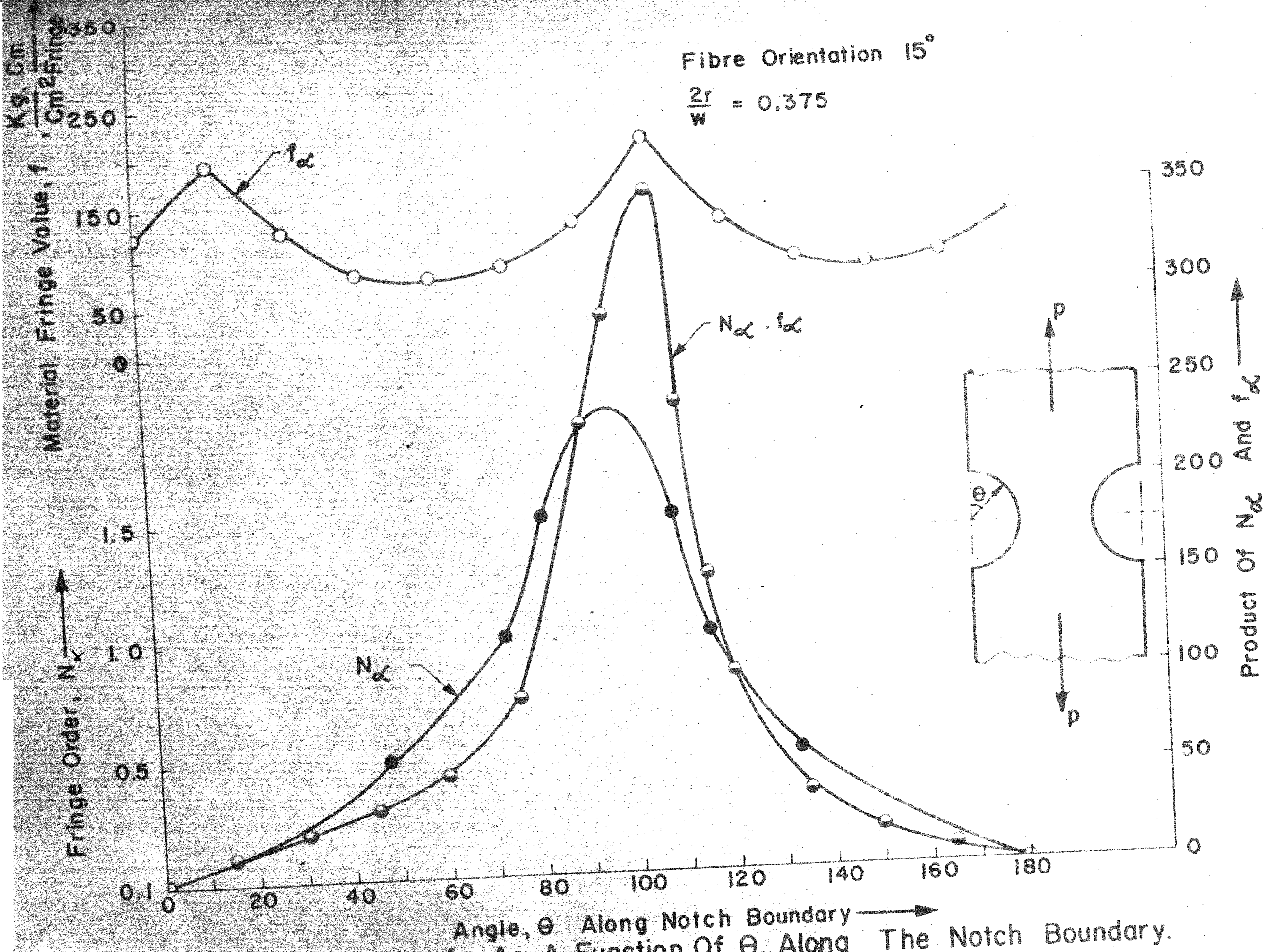

Fig.2.3 N_α, f_α And $N_\alpha \cdot f_\alpha$ As A Function Of θ, Along The Notch Boundary.

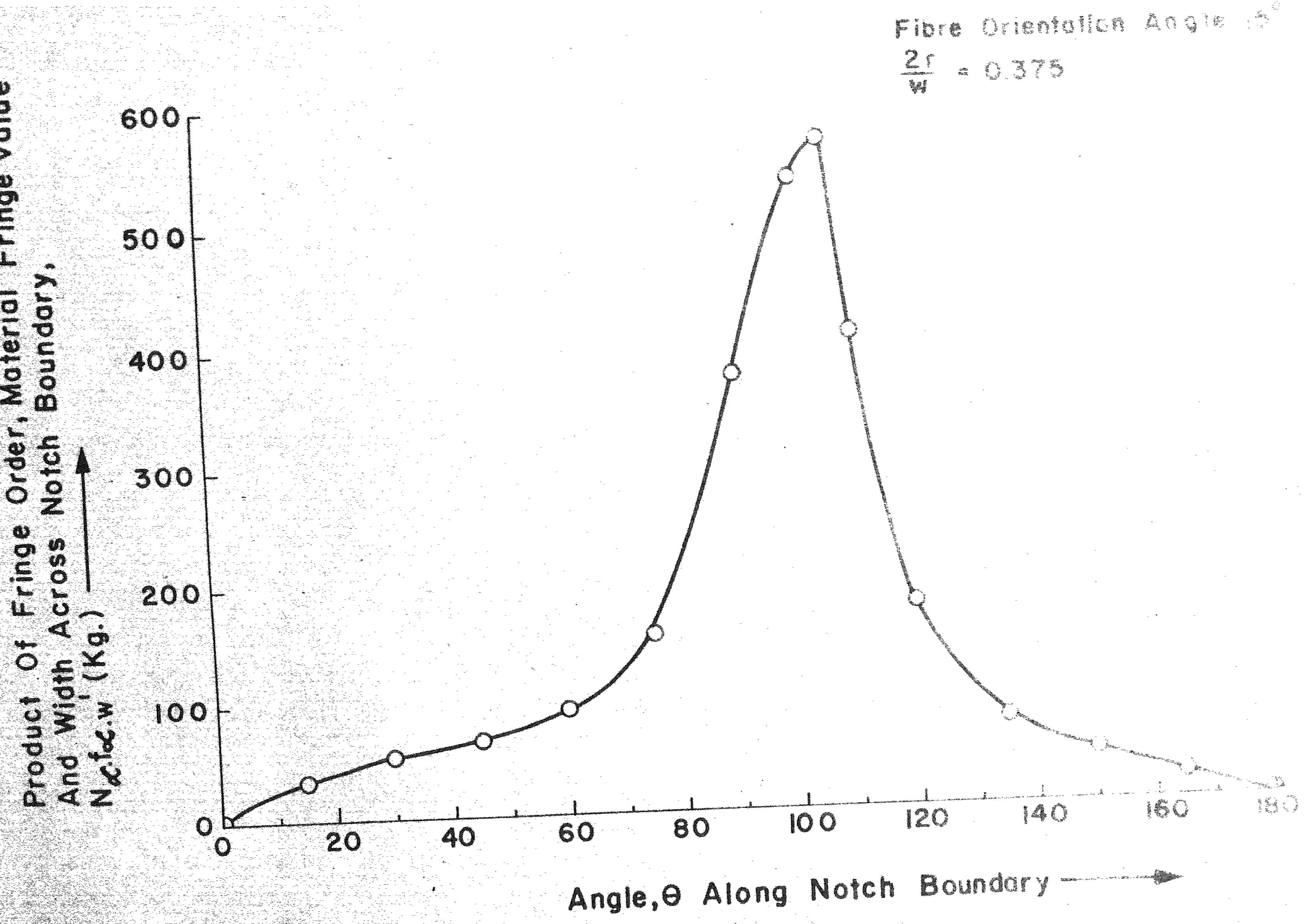

Fig.2.4 $N_\alpha \cdot f_\alpha \cdot w'$ As A Function Of θ, Along The Notch Boundary

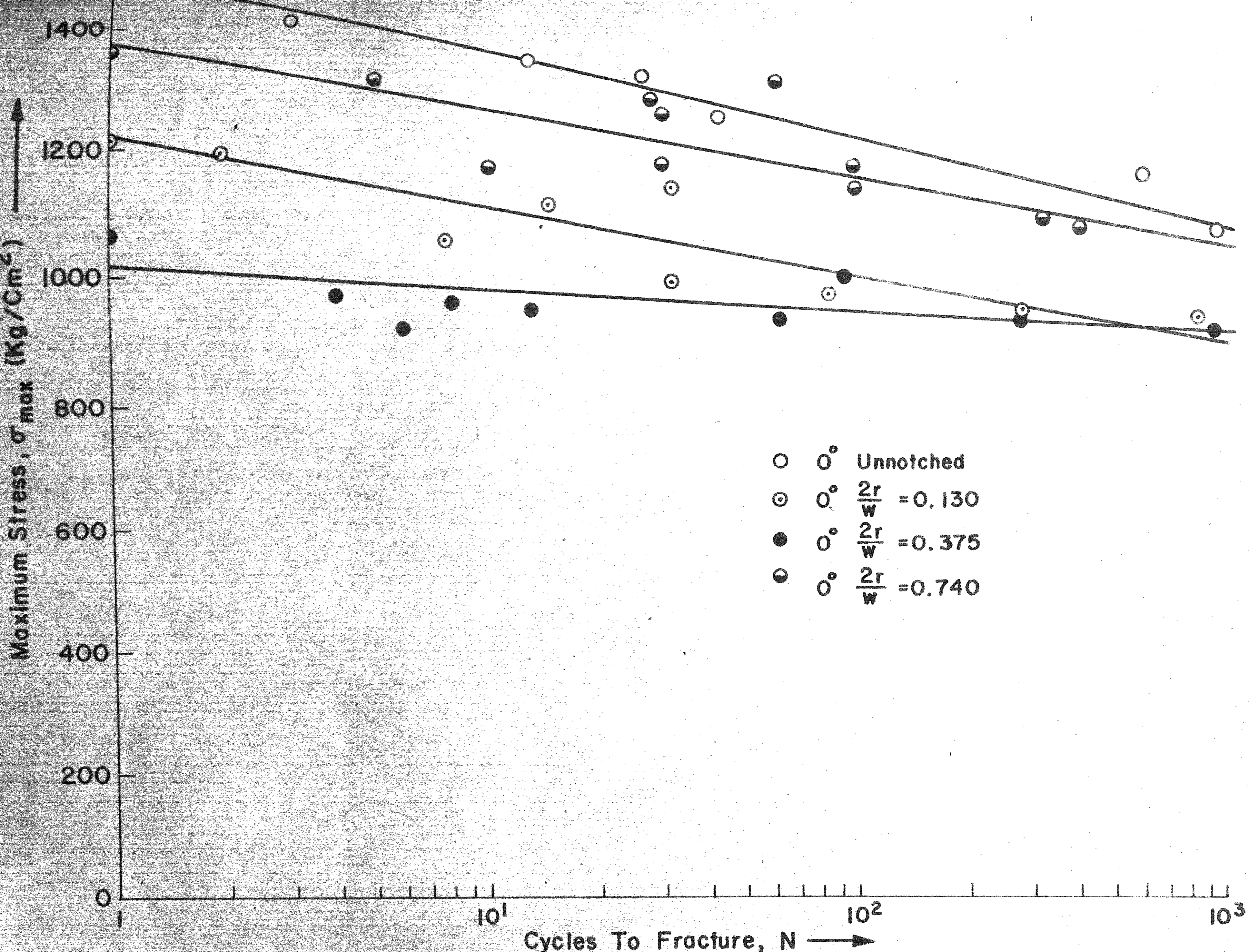

Fig. 3.1 S-Log. N Curve For 0° Fibre Orientation

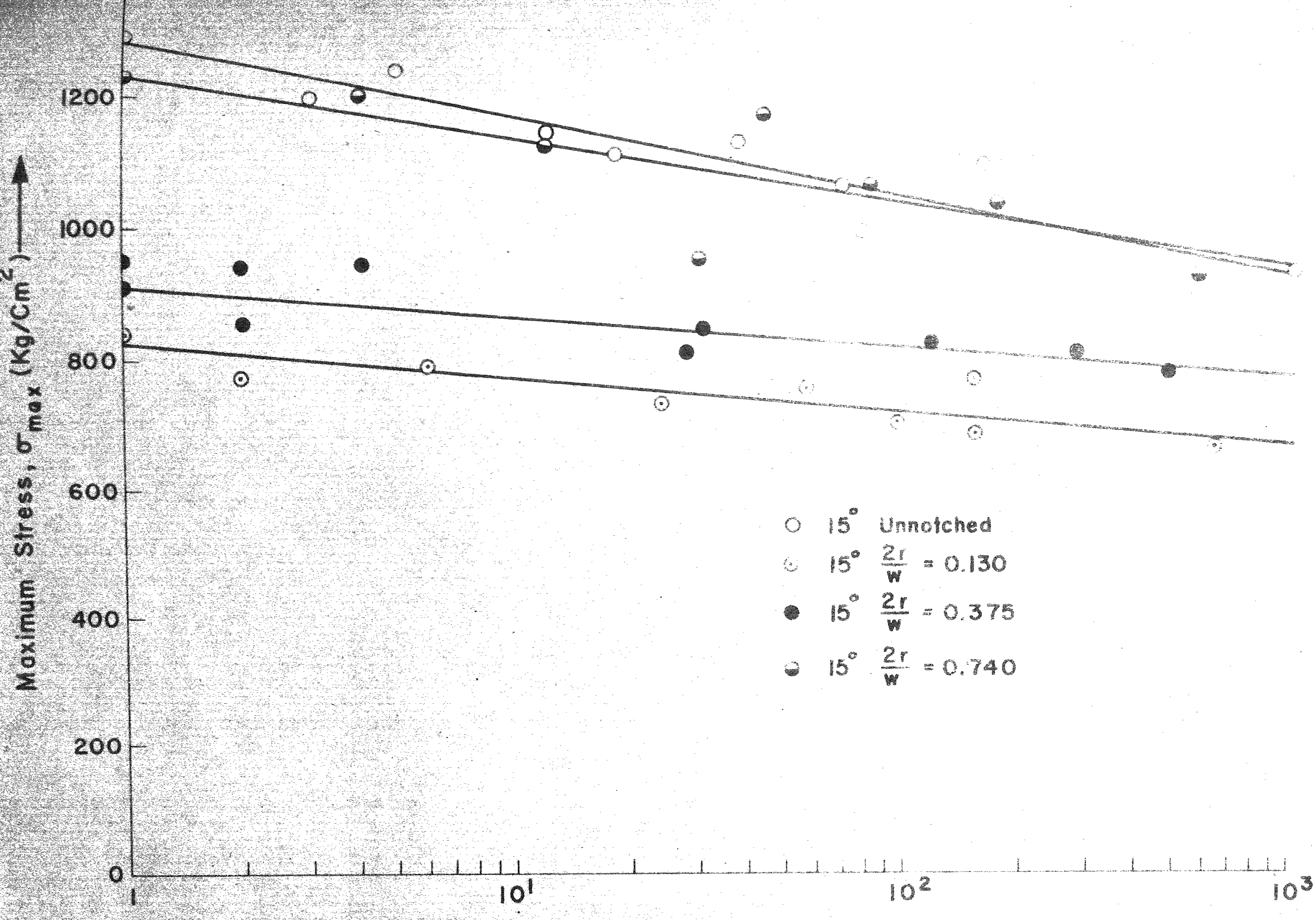

Fig. 3.2 S-Log N Curve For 15° Fibre Orientation

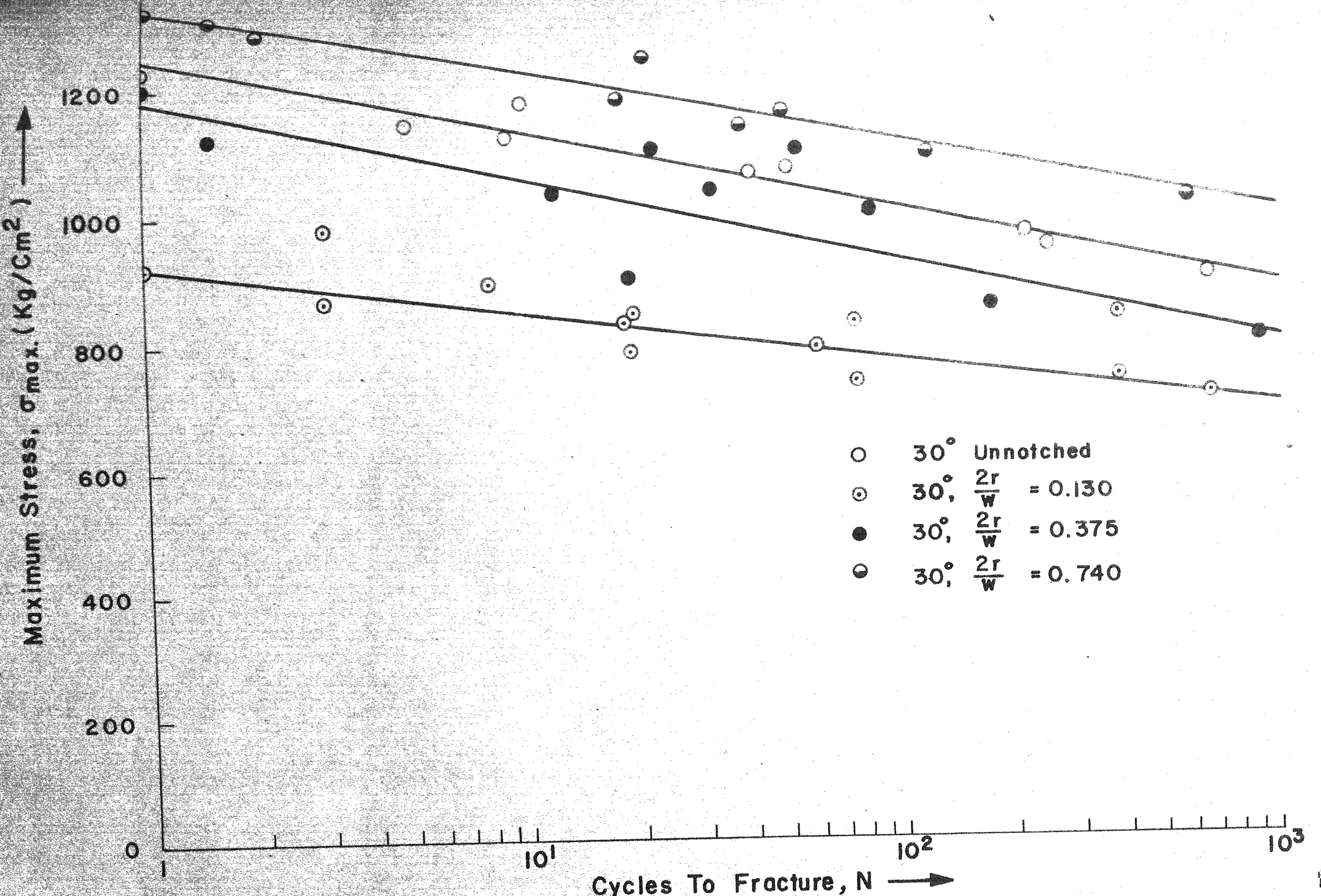

Fig. 3.3 S - Log N Curve For 30° Fibre Orientation

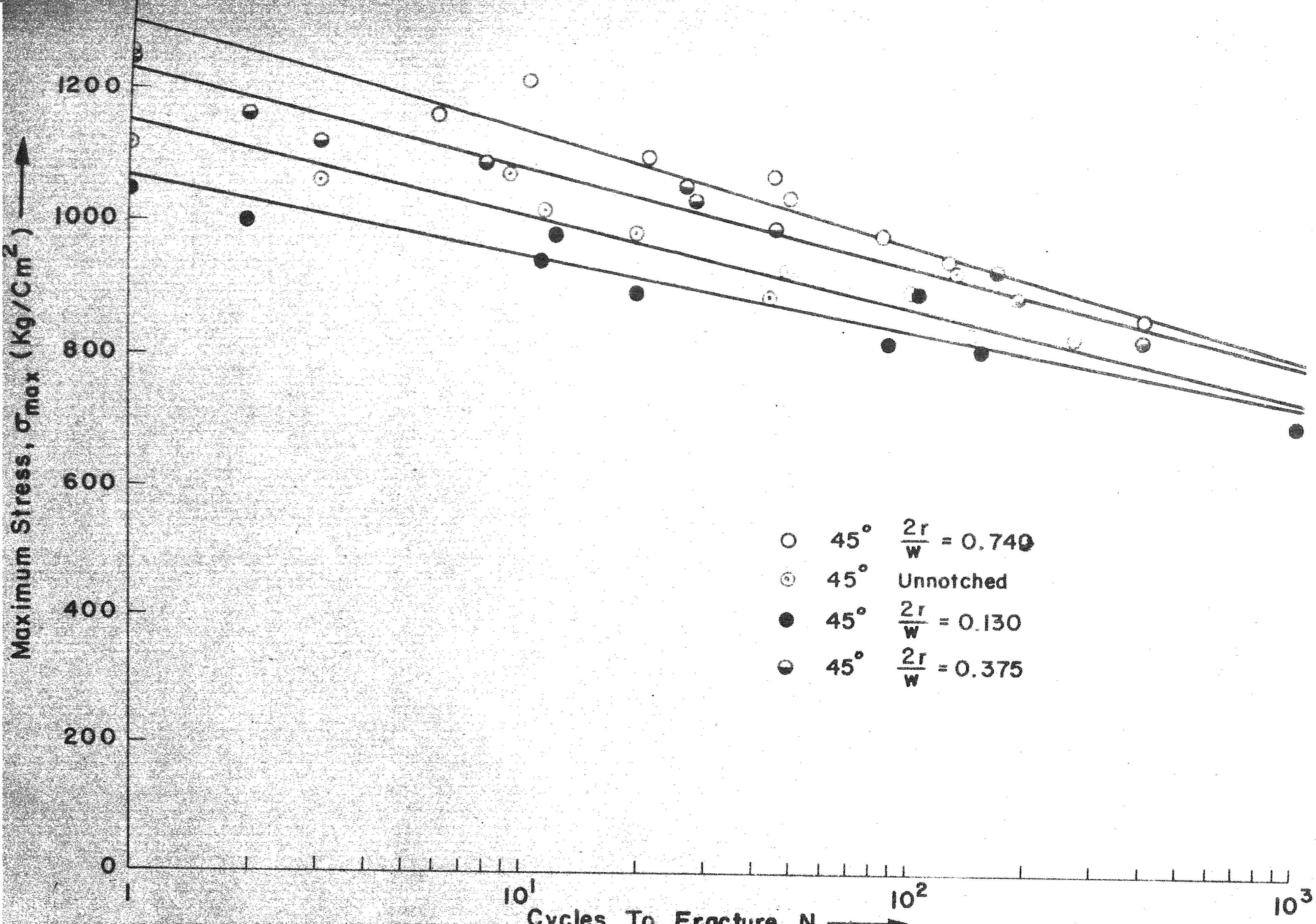

Fig. 3.4 S-Log N Curve For 45° Fibre Orientation

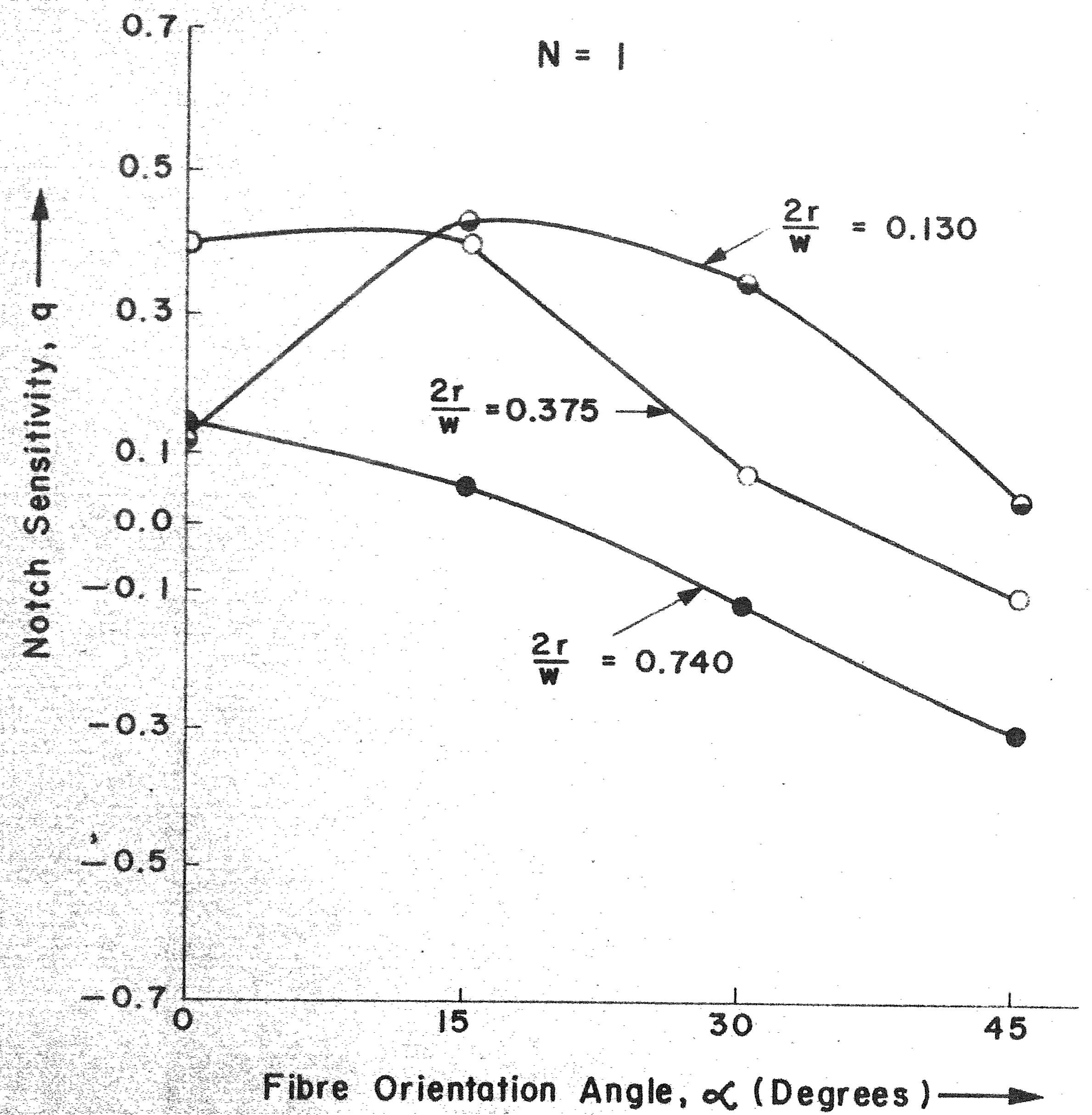

Fig. 3.5 Notch Sensitivity q, As A Function Of The Fibre Orientation Angle For N=1

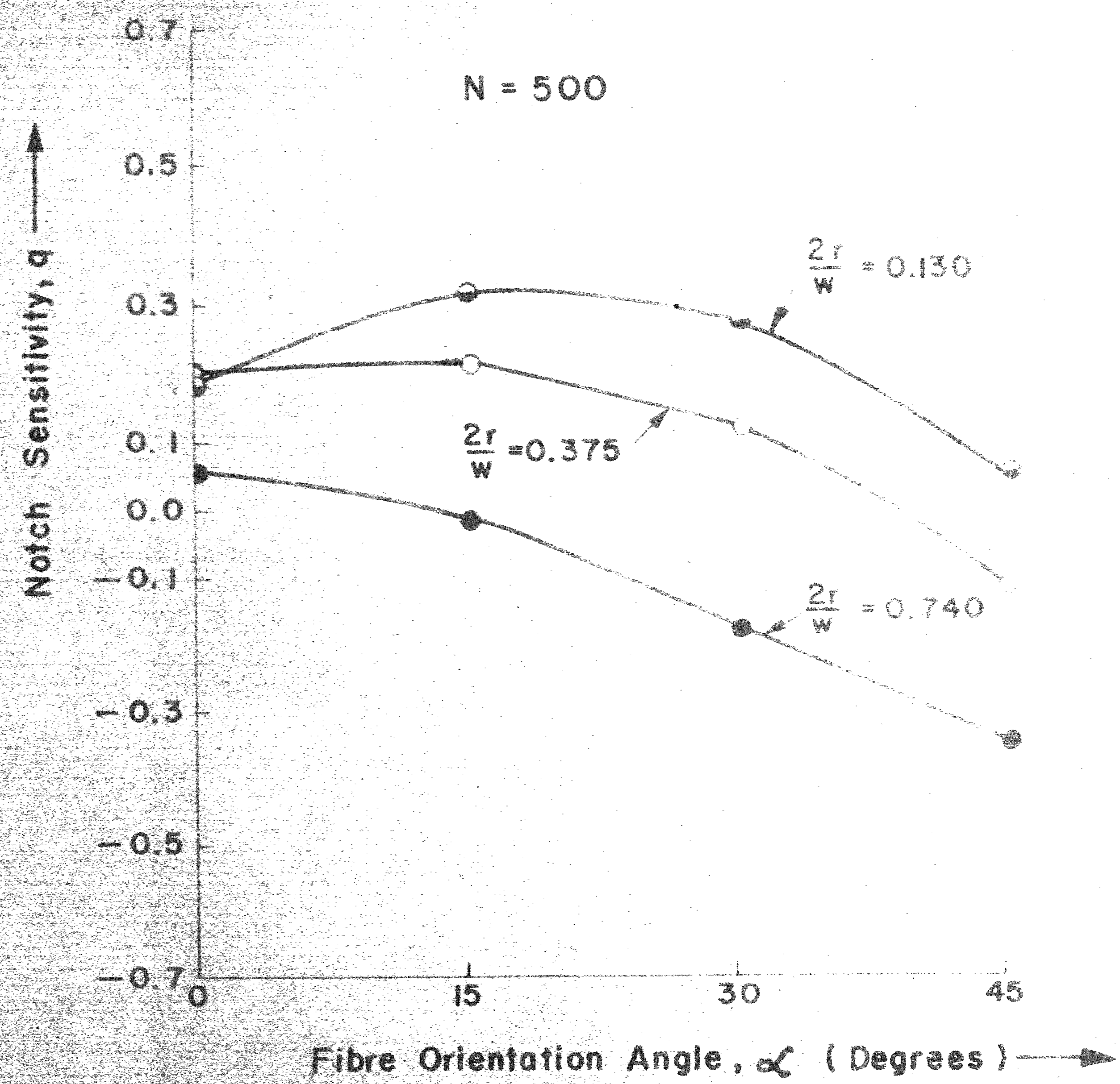

Fig.3.6 Notch Sensitivity q, As A Function Of The Fibre Orientation Angle For N = 500

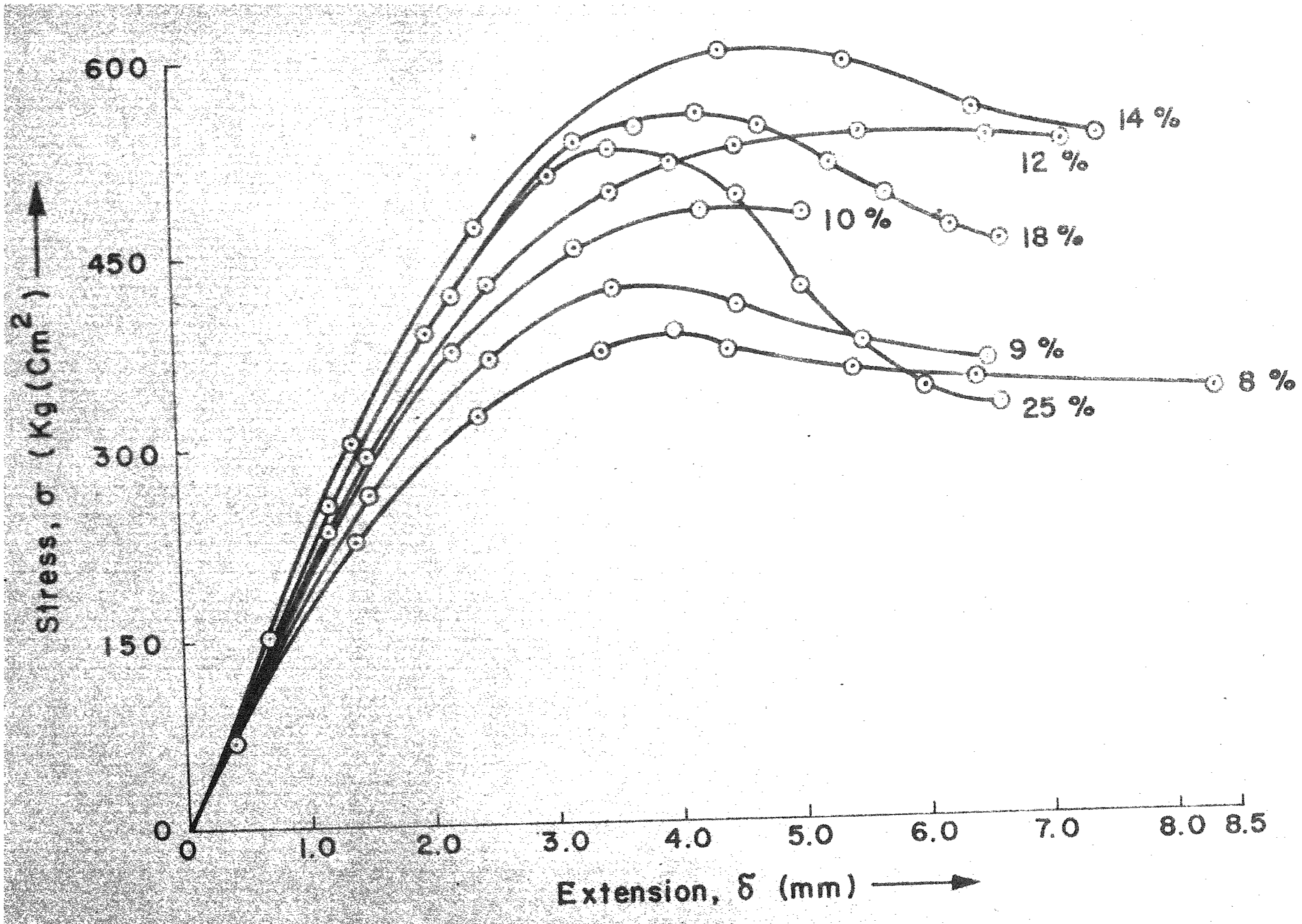

Fig.4.1 Stress-Extension Curve For Unnotched Specimens

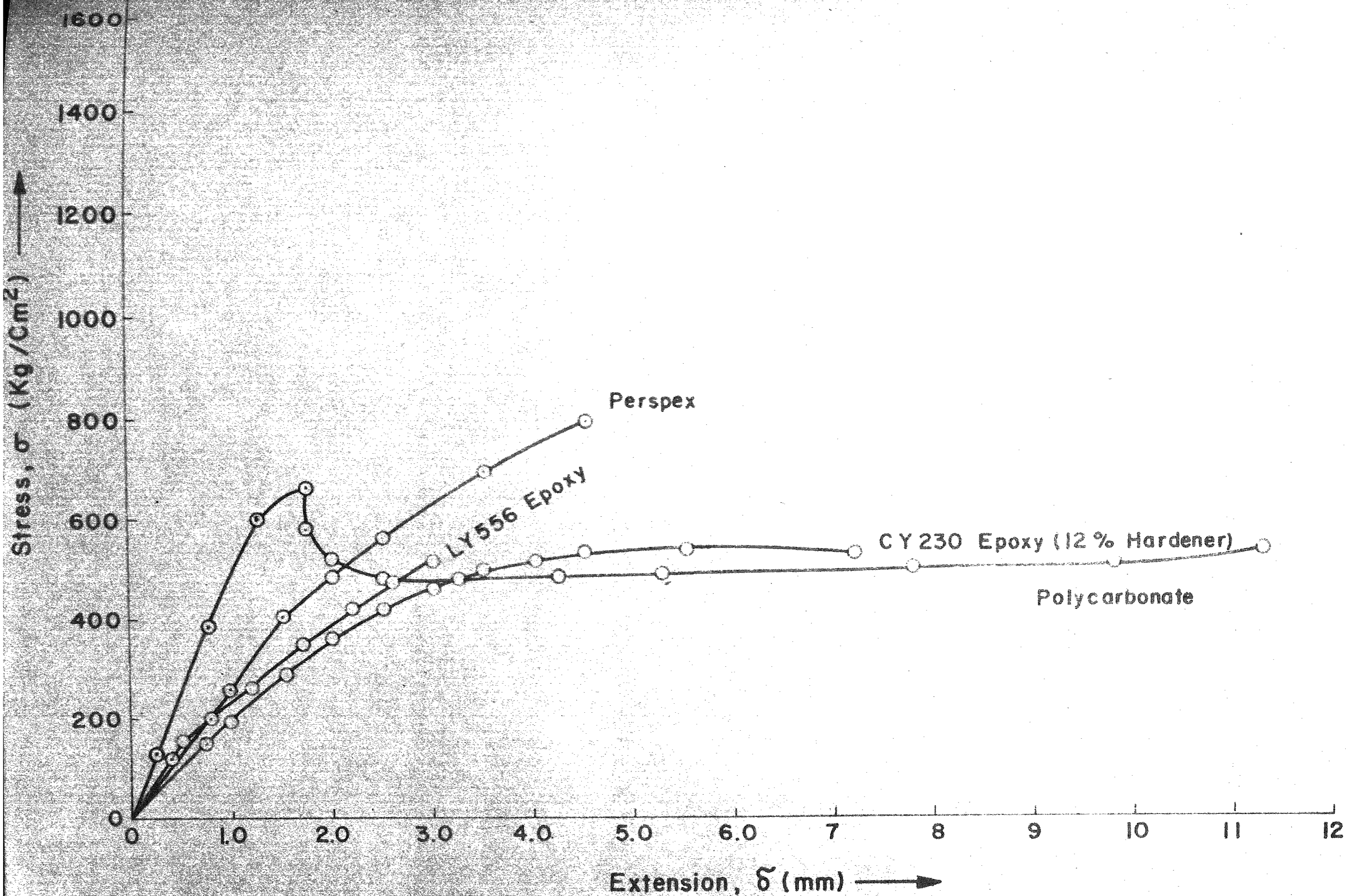

Fig. 4.2 Stress-Extension Curve For LY556, Perspex, Polycarbonate And Epoxy Matrix

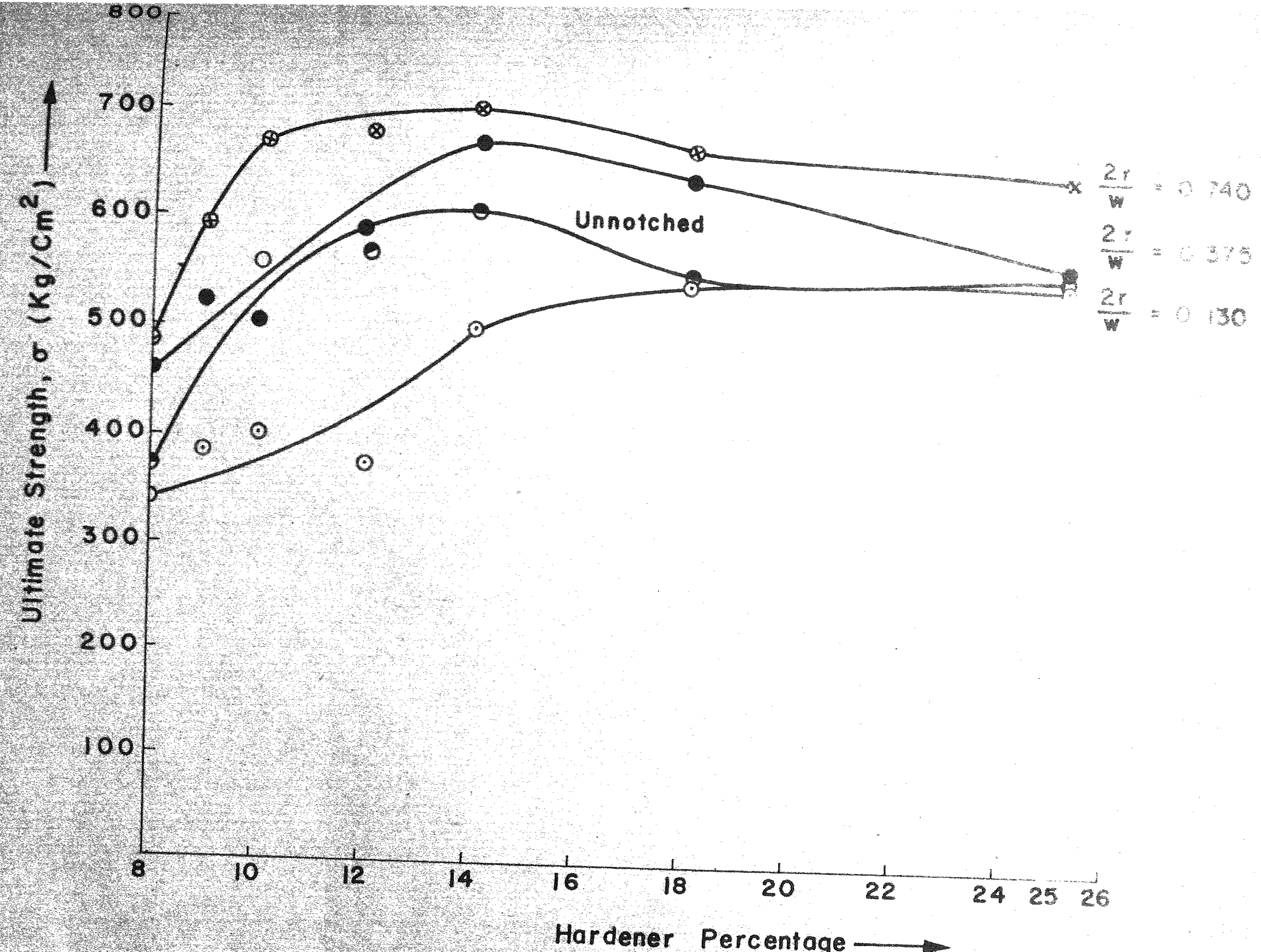

Fig. 4.3 Ultimate Strength As A Function Of Hardener Percentages

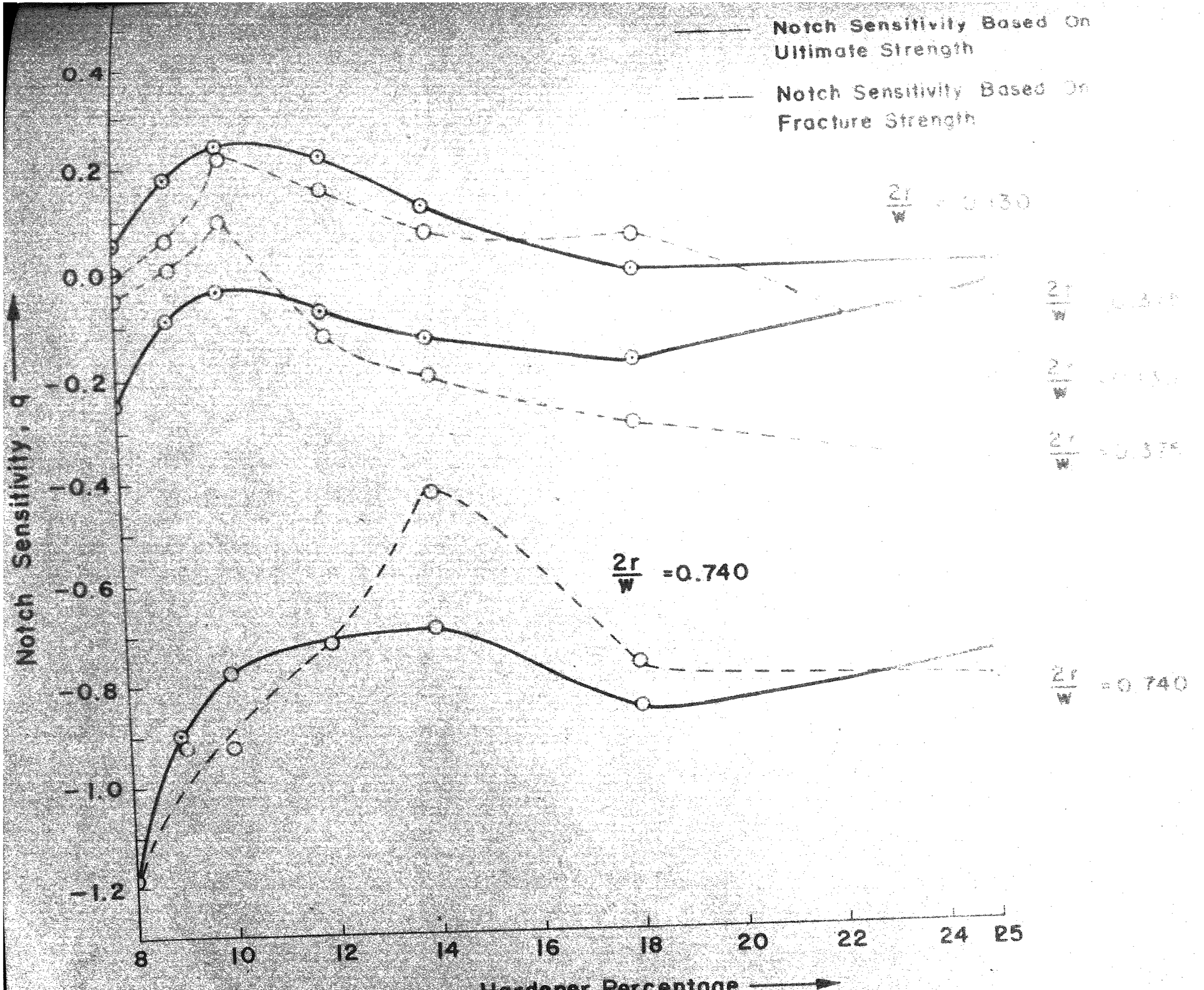

Fig. 4.4 Notch Sensitivity Of CY 230 Resin As A Function Of Hardener Percentages

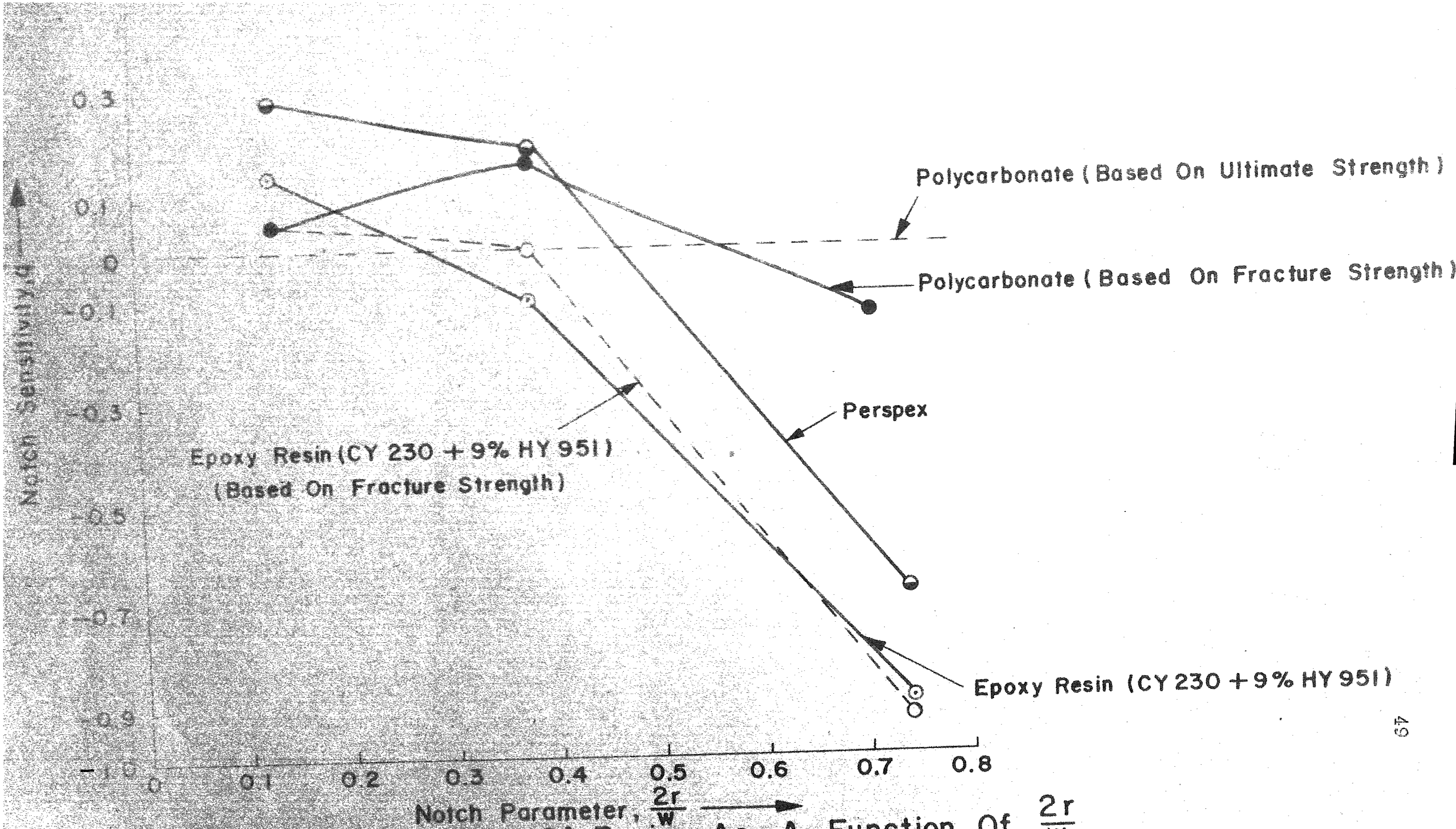

Fig. 4.5 Notch Sensitivity Of Resins As A Function Of $\frac{2r}{w}$

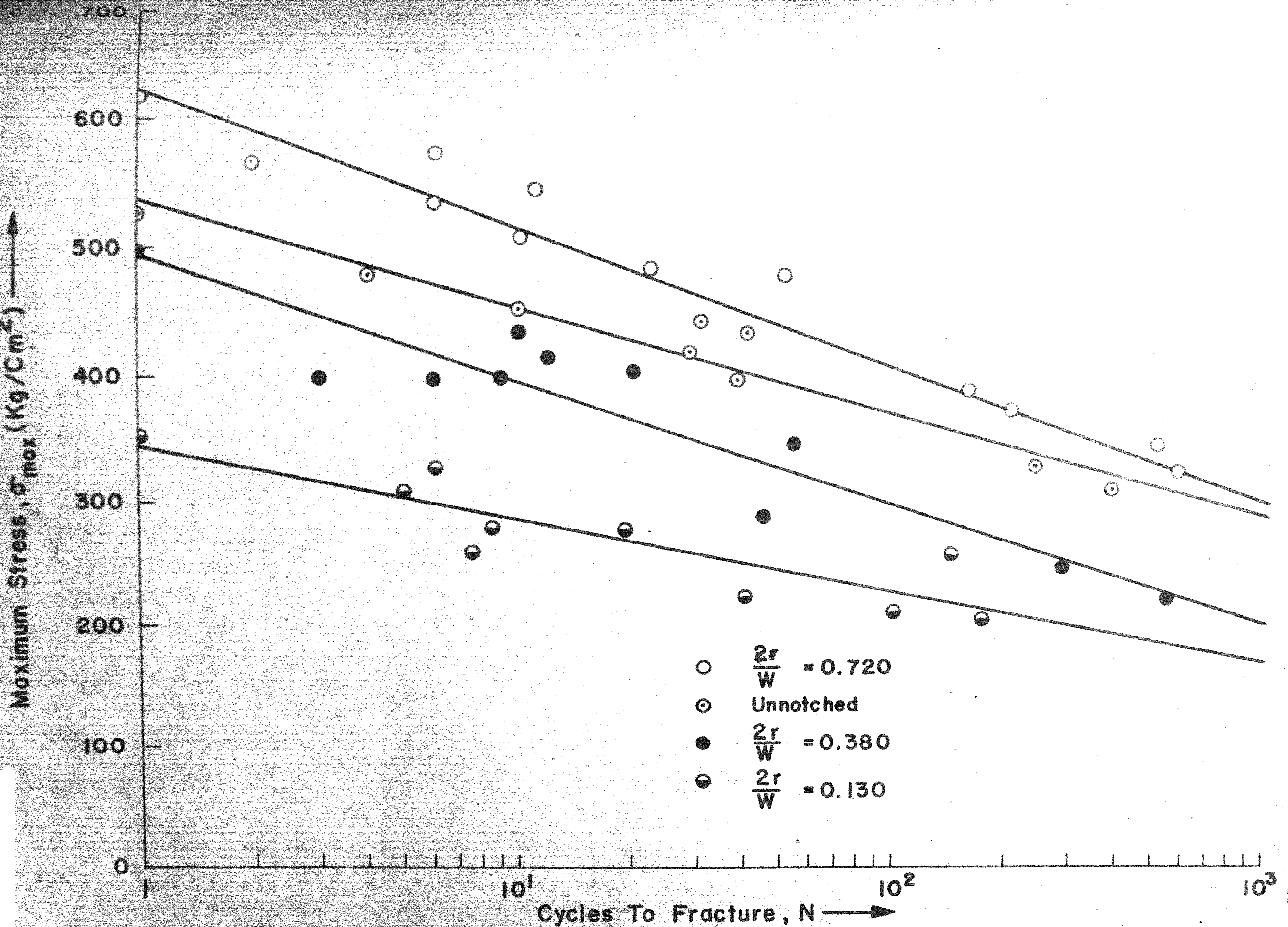

Fig. 4.6 S - log N Curve For An Epoxy Matrix (CY 230 + 12 % Hy 951)

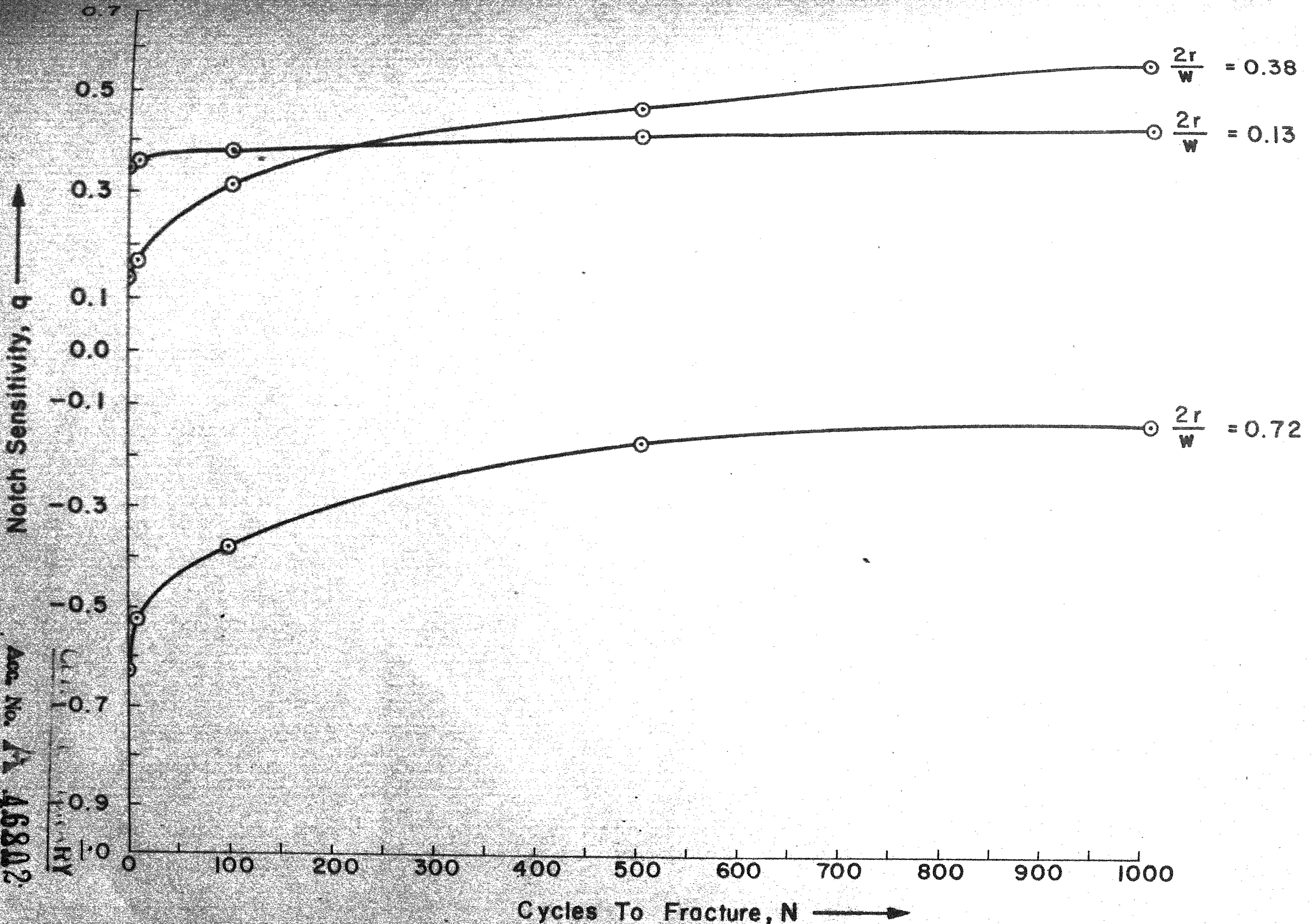

Fig. 4.7 Notch Sensitivity Of CY 230 Resin As A Function Of Cyclic Life

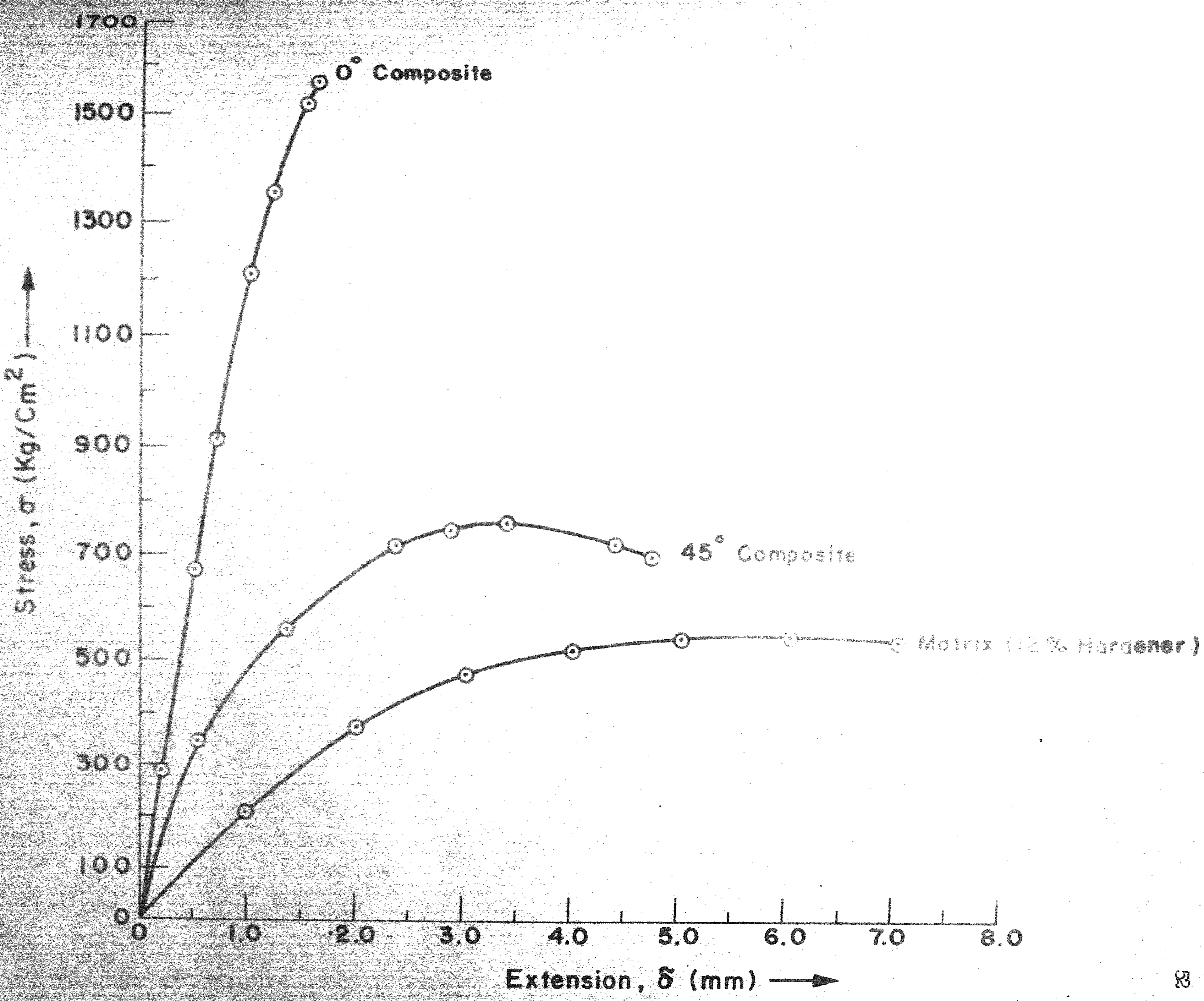

Fig. 5.1 Stress Extension Diagram

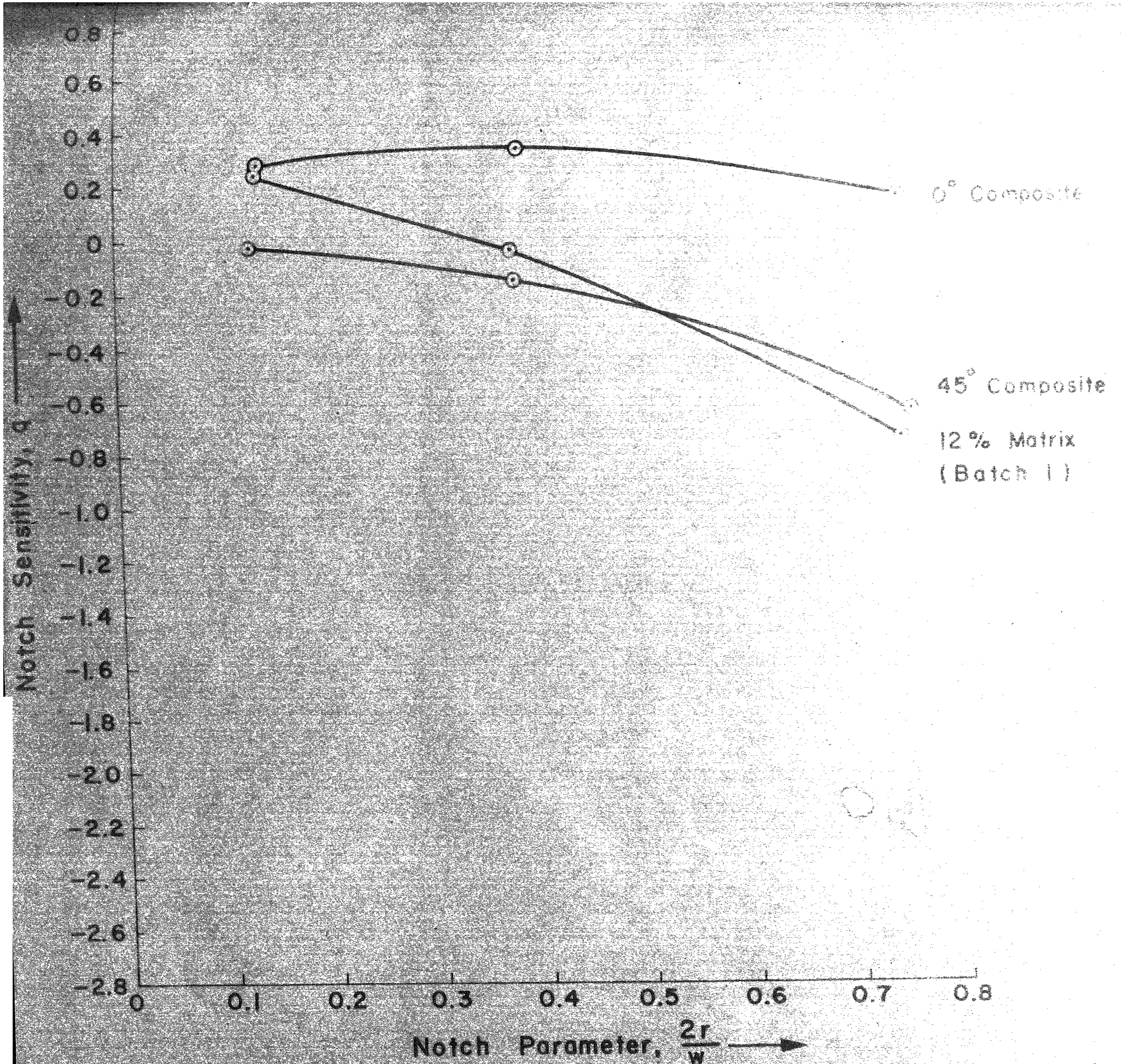

Fig.5.2 Notch Sensitivity Of Resin And Composite As A Function Of 2r/w

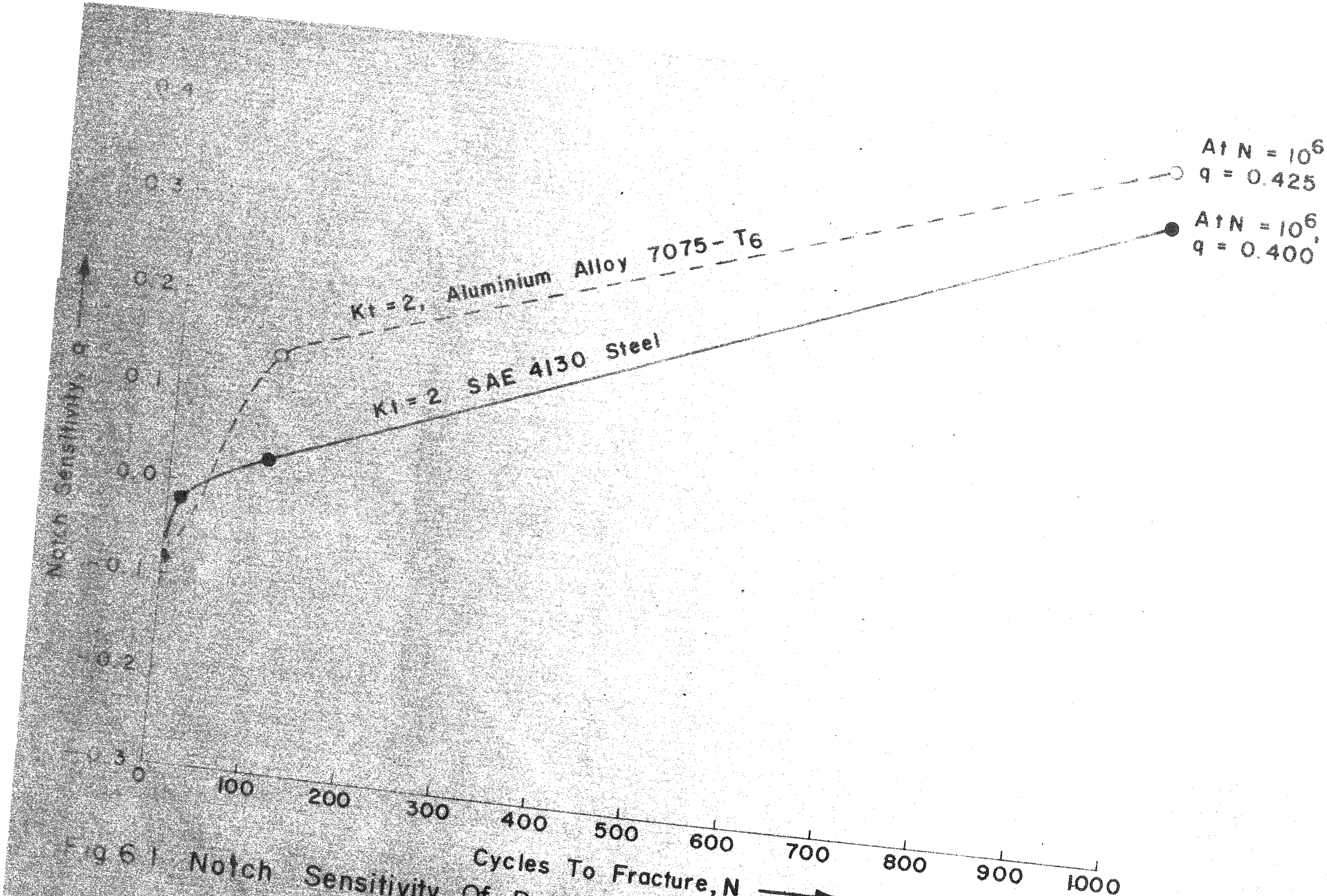

Fig 6.1 Notch Sensitivity Of Ductile Metals As A Function Of Cyclic Life